

ON THE SUPPORT OF NEUTRALS AGAINST GRAVITY IN SOLAR PROMINENCES

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ABSTRACT

Cool and dense prominences found in the solar atmosphere are known to be partially ionized because of their relative low temperature. In this Letter, we address the long-standing problem of how the neutral component of the plasma in prominences is supported against gravity. Using the multiple fluid approach we solve the time-dependent equations in two dimensions considering the frictional coupling between the neutral and ionized components of the magnetized plasma representative of a solar prominence embedded in a hot coronal environment. We demonstrate that given an initial density enhancement in the two fluids, representing the body of the prominence, the system is able to relax in the vicinity of magnetic dips to a stationary state in which both neutrals and ionized species are dynamically suspended above the photosphere. Two different coupling processes are considered in this study, collisions between ions and neutrals and charge exchange interactions. We find that for realistic conditions ions are essentially static while neutrals have a very small downflow velocity. The coupling between ions and neutrals is so strong at the prominence body that the behavior is similar to that of a single fluid with an effective density equal to the sum of the ion and neutral species. We also find that the charge exchange mechanism is about three times more efficient sustaining neutrals than elastic scattering of ions with neutrals.

Subject headings: plasmas — magnetic fields — Sun: corona

1. INTRODUCTION

Traditionally the problem of solar prominence support is described in terms of the magnetic force that balances the solar gravitational force. In the existing models it is assumed that the prominence plasma is fully ionized. However, observations of the prominence body in H α , which is an excitation line, suggest that the observed plasma can not be fully ionized. The same happens for prominence observations in the He I 10830 Å line. At a temperature of 20,000 K, typical of the prominence corona transition region (PCTR), we already have ionized H, ionized He and also ionized Ca. Thus, the support of both the ionized and neutral components is required. The main problem is that the neutral component is not directly affected by the restoring magnetic forces that can balance gravity.

In the past it has been proposed that the frictional coupling between neutrals and ions through elastic collisions might play a role in the support of prominences. Mercier & Heyvaerts (1977) examined the relative downward diffusion of neutral atoms due to gravity and taking into account the magnetic field. These authors found that the resulting downward velocity is irrelevant to explain the mass loss in prominences. Bakhareva et al. (1992) did the first attempt to construct a model based on the one-dimensional Kippenhahn-Schlüter solutions including ion-neutral collisions and provided some details about the dynamical regimes of prominence evolution. Pécseli & Engvold (2000) suggested that wave damping caused predominantly by ion-neutral collisions in the prominence core may balance the acceleration of gravity. Gilbert et al. (2002) have shown that the draining effect for a hydrogen-helium plasma is rather small, specially for the hydrogen that moves down in the di-

rection of the photosphere at a typical velocity of only 3.7 ms^{-1} . The results of these works indicate that ion-neutral coupling may be quite relevant to sustain neutrals, nevertheless, a consistent study taking into account frictional coupling, magnetic forces, and gravity has not been developed so far.

Another mechanism that provides a frictional force is the resonant charge exchange process. Contrary to the elastic scattering between ions and neutrals, charge exchange collisions are not identity-preserving. For hydrogen an energetic proton captures the electron from a lower-energy neutral producing an energetic neutral which has essentially the same energy as the incident proton. The reader is referred to Goldston & Rutherford (1995) for details about this process. Leake et al. (2013) has shown that under chromospheric conditions this process increases the collisional coupling between ions and neutrals. It is therefore logical to think that this mechanism can be also relevant under prominence conditions.

In the present Letter we follow an approach similar to the one described in Terradas et al. (2013) for a fully ionized plasma and is based on solving the time-dependent problem in a two-dimensional geometry with a magnetic field that incorporates dips. The main difference is in the injection of a plasma dominated by neutrals at the core of the prominence. With the two-fluid approximation the effects of ion-neutral collisions and charge exchange collisions are properly incorporated to the model. These mechanisms provide a redistribution of momentum of the species and change the force balance in the system. This is the crucial step to accomplish a new stationary state that is in dynamical equilibrium.

2. BASIC TWO-FLUID EQUATIONS

We use the most simplified version of the two-fluid equations including ion-neutral collisions and charge ex-

change collisions. For the ion-electron fluid we have the equations of continuity, momentum, pressure, and magnetic induction,

$$\frac{\partial \rho_i}{\partial t} = -\nabla \cdot (\rho_i \mathbf{v}_i), \quad (1)$$

$$\frac{\partial(\rho_i \mathbf{v}_i)}{\partial t} = -\nabla \cdot \left(\rho_i \mathbf{v}_i \mathbf{v}_i + p_{ie} \mathbf{I} - \mathbf{B} \mathbf{B} + \frac{1}{2} B^2 \mathbf{I} \right) + \rho_i \mathbf{g} - \alpha_{in} (\mathbf{v}_i - \mathbf{v}_n) - \beta_{in}^{cx} (\mathbf{v}_i - \mathbf{v}_n), \quad (2)$$

$$\frac{\partial p_{ie}}{\partial t} = -(\mathbf{v}_i \cdot \nabla) p_{ie} - \gamma p_{ie} \nabla \cdot \mathbf{v}_i + (\gamma - 1) (W_{in} + W_{in}^{cx}), \quad (3)$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v}_i \times \mathbf{B}), \quad (4)$$

We have used the simplest version of the Ohm's law in which Ohmic resistivity, the Hall and battery terms are ignored since they are very small under typical prominence conditions.

For the fluid composed of neutrals we have

$$\frac{\partial \rho_n}{\partial t} = -\nabla \cdot (\rho_n \mathbf{v}_n), \quad (5)$$

$$\frac{\partial(\rho_n \mathbf{v}_n)}{\partial t} = -\nabla \cdot (\rho_n \mathbf{v}_n \mathbf{v}_n + p_n \mathbf{I}) + \rho_n \mathbf{g} + \alpha_{in} (\mathbf{v}_i - \mathbf{v}_n) + \beta_{in}^{cx} (\mathbf{v}_i - \mathbf{v}_n), \quad (6)$$

$$\frac{\partial p_n}{\partial t} = -(\mathbf{v}_n \cdot \nabla) p_n - \gamma p_n \nabla \cdot \mathbf{v}_n + (\gamma - 1) (W_{ni} + W_{ni}^{cx}). \quad (7)$$

In these equations all the variables have the usual meaning. We define the drift velocity as $\mathbf{v}_D \equiv \mathbf{v}_i - \mathbf{v}_n$. The coupling between the two fluids is through the parameters α_{in} and β_{in}^{cx} . The first parameter represents the friction coefficient due to collisions between ions and neutrals (e.g., Braginskii 1965; Chapman & Cowling 1970). For hydrogen and assuming that ions and electrons have the same temperature the friction coefficient is given by the following expression

$$\alpha_{in} = \rho_i \rho_n \frac{1}{2m_p} \sigma_{in} \sqrt{\frac{4}{\pi} (v_{Tie}^2 + v_{Tn}^2)}, \quad (8)$$

where m_p is the proton mass and σ_{in} is the momentum transfer cross section, taken to be equal to 10^{-18}m^2 in this work (see Vranjes & Krstic 2013). The thermal speed of the different species is given by $v_T = \sqrt{2k_B T / m_p}$ where T is the temperature. It is useful to define the collision frequency between neutrals and ions as $\nu_{ni} = \alpha_{in} / \rho_n$. The maximum collision frequency in our configuration is $\nu_{ni} = 118 \text{Hz}$.

The second parameter, β_{in}^{cx} , is responsible for the charge exchange collisions and is given by the following expression (see Pauls et al. 1995; Meier 2011)

$$\beta_{in}^{cx} = \rho_i \rho_n \frac{1}{m_p} \sigma_{cx} \left(\sqrt{\frac{4}{\pi} (v_{Tie}^2 + v_{Tn}^2) + v_D^2} + \frac{v_{Tn}^2}{\sqrt{4 \left(\frac{4}{\pi} v_{Tie}^2 + v_D^2 \right) + \frac{9\pi}{4} v_{Tn}^2}} \right). \quad (9)$$

For interactions between protons and neutral hydrogen the cross section, σ_{cx} , is around 10^{-18}m^2 (see Meier & Shumlak 2012). Hence, the cross sections associated to elastic collisions and charge exchange collisions are approximately the same.

The terms W_{in} , W_{ni} , W_{in}^{cx} , and W_{ni}^{cx} in the pressure equations contain frictional heating and thermal transfer between the two populations associated to the two frictional mechanisms. The explicit form of $W_{in} = -W_{ni}$ can be found in, for example, Draine (1986) or Leake et al. (2014). The expressions for $W_{in}^{cx} = -W_{ni}^{cx}$, which are complex because the charge exchange physics is more complicated, can be found in the works of Meier (2011) and Leake et al. (2012). Because of the thermal transfer between the species included in these terms the temperatures of ions and neutrals will tend to be equal on short time scales.

Equations (8)-(9) indicate that the friction coefficients depend essentially on the density and pressure of the individual species (i.e., the thermal speed). Since the coefficients depend on the local plasma parameters they also vary in space and time during the evolution, allowing us to model self-consistently the coupling between ions and neutrals.

From Eqs. (2) and (6) we have that the force between the fluids is proportional to the difference in velocity between ions and neutrals, \mathbf{v}_D . Static stationary solutions are simply not possible. If neutrals are sustained against gravity it means that there must be a flow that provides the required frictional restoring force. The question is whether the flow produces an important draining effect of neutrals from the prominence body.

3. INITIAL CONDITIONS AND METHOD

In our model the density of ions and neutrals is constructed using a static background plus a localized enhancement representing the prominence. For the background we assume a stratified atmosphere for ions with a scale height characteristic of 10^6K , with gravity ($g = 274 \text{m s}^{-2}$) pointing in the negative z -direction.

The prominence is represented by a large density enhancement respect to the background (see Terradas et al. 2013), imposing that its maximum is 100 times larger than the coronal density. This enhancement is assumed to be composed by 75% of neutrals and 25% of ions. These percentages are consistent with the ionization models of Gouttebroze & Labrosse (2009) (see middle panel of their Figure 1). Regarding the spatial structure of the enhancements for both ions and neutrals is given by a two-dimensional Gaussian with a characteristic width a and b in the x and z -directions, respectively. We use that $a = 0.3 L_0$ and $b = 0.6 L_0$.

For the magnetic configuration we use a force-free quadrupolar structure described in Terradas et al. (2013). Magnetic dips are present in this topology (see Figure 1) and are important to achieve a sustained prominence. A small shear component is included in the model to avoid the plasma- β to be infinite at the base of the corona. We use a magnetic field of 50 G at this level which gives 10 G at the core of the prominence (the

plasma- β is around 0.1) and the changes in the magnetic field during the evolution are rather small.

The system of time-dependent nonlinear equations given by Eqs. (1)-(7) together with the initial conditions are solved in two-dimensions. We choose the following normalizing values for the length, $L_0 = 10^7$ m, and density, $\rho_0 = 5.2 \times 10^{-13} \text{ kg m}^{-3}$. The normalizing value for velocity is $c_{s0} = 1.66 \times 10^5 \text{ m s}^{-1}$. The simulation domain extends from $-6L_0$ to $6L_0$ in the x -direction and from 0 to $8L_0$ in the z -direction. We use 200×200 grid points. Line-tying conditions are imposed at $z = 0$ representing the base of the corona while extrapolated conditions are enforced at the lateral and upper boundaries. The inclusion of the frictional terms imposes a strong limitation on the time steps required to properly resolve the short diffusion time scales.

4. RESULTS

A representative simulation with the parameters given in the previous section is described here. For a better understanding of the results we first neglect charge exchange collisions, which will be included later, and concentrate on elastic scattering between ions and neutrals.

4.1. Ion-neutral collisions

From the analysis of the time-dependent simulations we find several evidences about the support of neutrals located at the core of the prominence. As an example, we have plotted in Figure 1 top panel, the two-dimensional distribution of the two plasma densities after only 4.8 min of evolution. The ion-neutral fluid and neutrals are essentially superimposed, and the compact spatial shape of the densities found in this figure is very similar to that at the beginning of the simulation meaning that the mass redistribution is rather small in the configuration. On the contrary, in Figure 1 bottom panel, the results of the same simulation are shown but with a reduced maximum value for α_{in} (ten times smaller than in top panel). The behavior of the system is very different with respect to the previous case. Neutrals are falling quite quickly and diffusing across the magnetic field. A sustained situation for neutrals is not achieved in this case.

We return to the case studied in Figure 1 top panel. We have allowed the system to evolve for more than 10 hours, and the geometrical changes found at the prominence core are very small. In fact neutrals are moving downwards but with such small velocity that makes, to all practical purposes, difficult to distinguish from a static situation. These results clearly indicate that a sustained partially ionized plasma is a feasible configuration. The crucial point is that the friction coefficient is very large at the core of the prominence and the coupling between ions and neutrals is very strong. Essentially the multi-component plasma behaves as a single fluid at the prominence body and this means that the velocities for the two plasma components are very similar. Thus, the drift velocity is rather small, but since the frictional coefficient is very large the frictional force, which is simply the product $\alpha_{\text{in}} \mathbf{v}_D$, is sufficient to balance gravity. This drift velocity, \mathbf{v}_D , is always positive and therefore the frictional force counterbalances the gravity force pointing downwards and acting on neutrals. The gas pressure at the center of the prominence has a maximum, and the pressure gradient is zero. The first term on the right

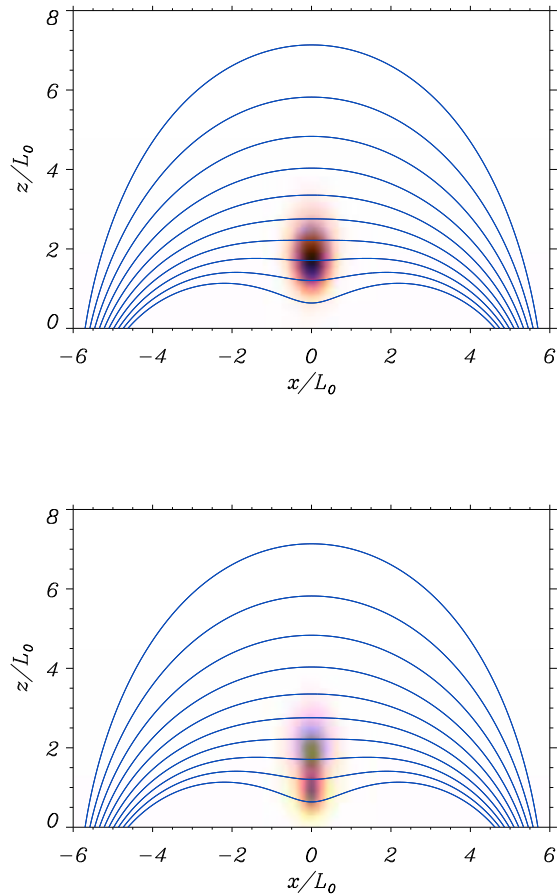


FIG. 1.— Magnetic field (blue lines) and density of the ion-neutral fluid (blue-green colors) and neutrals (yellow-pink colors) at a given time ($t = 4.8$ min). In the top panel the simulation corresponds to a maximum collision frequency of $\nu_{\text{ni}} = 8.5$ Hz, approaching to the strong coupled case. For the bottom panel $\nu_{\text{ni}} = 0.8$ Hz, the weak coupling between the ionized plasma and neutrals produces the diffusion of neutrals across the magnetic field.

hand side of Eq. (6) is therefore negligible since $\rho_n v_{nz}^2$ is quite small (we concentrate only on the z -component). The remaining terms provide the force balance in the z -direction, meaning that $v_{Dz} \approx g/\nu_{\text{ni}}$ in agreement with the results of Gilbert et al. (2002); Gilbert (2011) based on simple assumptions and the balance in the momentum equation. This means that the drift velocity is inversely proportional to the neutral-ion frequency. So if the system is in a stationary state under balance of forces the stronger the coupling between the two-fluids (higher neutral-ion frequency) the smaller the vertical component of the drift velocity. In fact, the ionized plasma is in this regime essentially static ($v_{iz} \approx 0$), meaning that the downward velocity of neutrals is simply $v_{nz} \approx -g/\nu_{\text{ni}}$.

Now we turn our attention to the ionized plasma and consider Eq. (2). For the same reasons as before the gradient of the inertial and pressure terms is negligible but the magnetic term is very relevant. It provides the balance against the gravity term and the frictional force that now is pointing downwards. To have force balance the magnetic force must be equal to $\rho_i g + \alpha_{\text{in}} v_{Dz}$, which using

the previously estimated value for v_{Dz} , it reduces to the simple and illustrative expression $g/(\rho_i + \rho_n)$. The physical interpretation is clear. The ionized fluid is always supported by the magnetic field but if a neutral component is included in the model the only way to have a new balance of forces is to increase the restoring magnetic force in such a way that the weight of the two plasma components is compensated by the deformation of the magnetic field. This result is only valid when the two fluids are strongly coupled, and this is true at the core of the prominence body.

We have explored the dependence of the results on the crucial magnitude of our model, namely α_{in} or equivalently ν_{ni} . We have artificially imposed the maximum of this parameter and have performed different numerical experiments. The results are shown in Figure 2. When ν_{ni} is around three orders of magnitude below the maximum value given by Eq. (8) ($\nu_{ni} = 118 \text{ Hz}$), neutrals are weakly coupled with the ion-electron fluid and they essentially fall down rapidly toward the base of the corona (see Figure 1 bottom panel). However, when this parameter is raised a new dynamical equilibrium is accomplished with a reduced drift velocity. We have been able to check using the numerical results that the expression $v_{nz} \approx -g/\nu_{ni}$ is satisfied (compare circles with the dashed line), which is a further confirmation that the system is under a dynamical balance. In fact, due to numerical issues related to the size of the time-step in the simulations when the collision frequency is large, we have been forced to fix a maximum collision frequency below the maximum value inferred from Eq. (8). Nevertheless from Figure 2 we see that we are approaching to the analytic results.

Using the maximum collision frequency ($\nu_{ni} = 118 \text{ Hz}$) in our configuration, and the expression for the velocity drift, we obtain that the draining of neutrals takes place at a speed of only $v_{nz0} \approx -2.3 \text{ m s}^{-1}$ (see the dotted vertical line in Figure 2). This is a very low velocity and is in good agreement with the value inferred by Gilbert et al. (2002) ($v_{nz0} \approx -3.7 \text{ m s}^{-1}$). Hence, the draining of neutrals from the prominence core proceeds on very large time-scales which are of the order of months using the simple time estimate $2L_0/|v_{nz0}|$ (the time required for the neutrals located at a height $2L_0$ to reach the base of the corona moving at a constant velocity $|v_{nz0}|$).

In the two-fluid approach the heating rate due to the conversion of kinetic energy is simply $\alpha_{in} \mathbf{v}_D^2$. Using the expression for the drift velocity we obtain $\rho_n g^2 / \nu_{ni}$. This magnitude at the core of the prominence (using the maximum frequency of 118 Hz) gives a heating rate which is typically of the order of $10^{-8} \text{ J m}^{-3} \text{ s}^{-1}$. Hence, heating by frictional collisions is quite irrelevant.

4.2. Charge exchange collisions

Now the terms associated to charge exchange interactions are activated in the simulations. These terms increase the frictional coupling between the species, and this can be easily inferred from the comparison of Eqs. (8) and (9). Neglecting the drift velocity in front of the thermal velocities, and assuming that the thermal velocities of the ion-electron and neutral fluids are the same, it is straight forward to find that $\beta_{in}^{cx} \approx 2.72 \alpha_{in}$ (since the two processes have the same cross section). Thus, charge exchange collisions produce almost three times more fric-

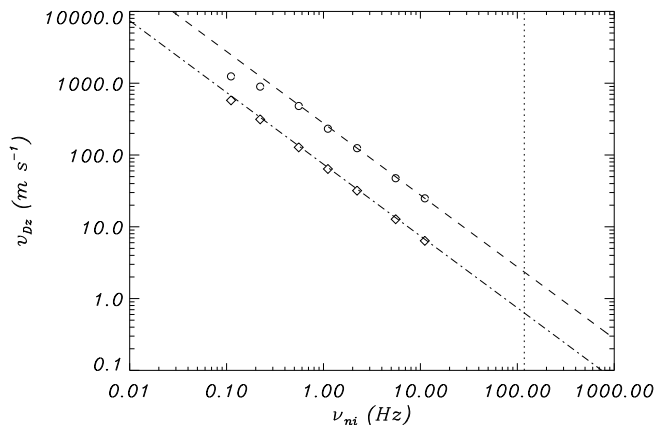


FIG. 2.— Drift velocity for different values of α_{in} (ν_{ni}) inferred from the simulations at the point $x = 0$, $z = 2L_0$. Circles correspond to elastic ion-neutral collisions while diamonds to elastic plus charge exchange collisions. The dashed line represent to the analytic approximation $v_{Dz} \approx g/\nu_{ni}$, while the dot-dashed line corresponds to the approximation $v_{Dz} \approx g/(3.72 \nu_{ni})$. The vertical dotted line is the maximum collision frequency.

tion than that of ion-neutral collisions. This means that the downward velocity of neutrals is further reduced by charge exchange interactions and the final expression is $v_{nz} \approx -g\rho_n/(\alpha_{in} + \beta_{in}^{cx}) \approx -g/(3.72 \nu_{ni})$. To test the assumptions made to derive this expression we have again changed the maximum collision frequency and have calculated from the simulations the numerical value of v_{nz} when both ion-neutral and charge exchange collisions are present. The results are overplotted in Figure 2 with diamonds. Once more the agreement between the simulations and the analytic approximation (plotted with a dot-dashed line) is remarkable.

5. DISCUSSION

In spite of the simplicity of our model it contains the very basic ingredients to demonstrate that the support of neutrals in solar prominences through frictional coupling is a viable mechanism. We have not tried to model the formation process and have concentrated mainly on the issue of the support of neutrals. We have found that as long as the friction coefficient is large, and the estimations of this coefficient under prominence conditions point in this direction, it is relatively easy to find a “dynamical equilibrium”. We have shown for the first time by solving the time-dependent problem that through the frictional coupling, magnetic forces rearrange to balance the gravity force acting on the joint mass of neutrals and ions. Interestingly, for hydrogen the friction coefficient for charge exchange collisions is three times larger than the friction coefficient for ion-neutral collisions. The nonstatic equilibrium is characterized by a rather small downflow velocity for neutrals, around 2.3 m s^{-1} , for ion-neutral collisions. But when charge exchange collisions are added to ion-neutral collisions this downflow velocity is reduced up to a factor four, since the net friction is increased. Therefore, the draining of neutrals from the prominence is not an important issue when the frictional

coupling between the species is strong. To all practical purposes, it would be difficult to distinguish a static situation from the steady-state situation obtained in this work with such low values of the drift velocity.

Many effects have been ignored in the present work. In particular, the ionization fraction does not change consistently because photoionization and recombination have been neglected. It is relatively simple to include recombination in the two-fluid equations but photoionization is much more difficult. To properly address this problem the full NLTE (non-local thermodynamic equilibrium) radiative transport equations should be coupled with the two-fluid equations and this is out of the scope of this work. Viscosity and other non-ideal effects have been neglected. It has also been assumed that the prominence is an isolated system, more representative of quiescent prominences, ignoring dynamical effects such as strong flows along the magnetic field that are often observed in active region prominences which could modify the drain-

ing rate of neutrals.

Finally, instead of 2D, 3D prominences models should be studied, since are able to develop several kinds of instabilities such as the magnetic Rayleigh-Taylor instability (see Hillier et al. 2011; Terradas et al. 2015). The effect of neutrals on this instability needs to be investigated further since the growth-rates can be significantly modified (see Díaz et al. 2012; Khomenko et al. 2014).

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